Phase Change Materials for Advanced Mars Thermal Control

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Abstract

Future missions to Mars for the 1998 launch opportunity and beyond will require advanced thermal control for electronics to minimize enclosure mass, power and volume. An additional requirement is that radioactive heating units (RHU) will not be available for future Mars missions. These strict requirements can be accomplished by integrating phase change. material (PCM) panels with aerogel insulation in a structural/ thermal enclosure for electronics and instruments. The aerogel insulation has extremely low thermal conductivity, and the PCM panels provide thermal capacitance. The advanced PCM panels consist of a sandwich panel design with an interlocking carbon fiber core which is filled with a suitable phase change material. The fibers provide structural stiffness, and prevent the PCM from forming voids or migration of voids by capillary action. With this design, a PCM mass fraction of 70% has been achieved. Included in this design is a diode heat pipe to recover thermal energy from radiators or other heat sources. This concept has been validated as a Warm Electronic Enclosure (WEE) in simulated Mats environmental condit ions. The WEE used dodecane as the phase change material (solid/liquid transition at -10 °C). The WEE consisted of a thermal insulation enclosure with six PCM panels on the interior. One of the PCM panel had an integrated diode heat pipe. The Mars 8 torr vacuum environment, and the diurnal temperature variation from 0 to -80 °C were simulated. The WEE was able to maintain interior temperatures within +/- 20 °C for a simulated 8 watt peak electronics power, and from 0° to -30 °C for a simulated 6.4 watt peak electronics power during sunlight operations.

introduction

The Martian environment provides a very wide variation in ambient temperature from day to night, Ground temperatures can reach as high as -20°C during the day and go down to 160 K at night depending on latitude and time of year (1). Most electronics developed for Earth application require operating temperatures in the range -40 to 40 °C, and have limits for survival in extreme temperatures. While. it is hoped that some day, special electronics will be developed which can survive low temperatures and possibly even operate at low temperatures, the continuing pressure to drive costs down on space missions usually implies that low-cost standard electronics developed for normal temperature operation will be employed on future Mars Landers. In addition, other components, particularly batteries lose performance as the temperature is lowered below -20 °C, and eventually become. non- operable at very low temperatures. Therefore, protecting elect ronics, batteries and other components from the low temperature night environment is a critical need of Mars missions. For the Viking Landers, Wilbert, *et.al.* conducted evaluated foam insulations, fibrous, powders and multilayer insulation (MLI) for thermal control(2). The result of that study was the primary use of several inches of foam insulation and some MLI on the Viking landers. Other studies of thermal control for Mars in that time period assumed a foam insulation of 3 to 4 inches thick for potential Mars missions (3,4), as well as considering phase change materials, heat pipes, louvers and other thermal control hardware. in those studies they did not have severe constraints on mass, volume or power. Future programs propose smaller, more mass, power and volume limited landers.

NASA currently has plans to launch missions to place a lander or other scientific instruments such as surface penetrators on Mars in 1996, 1998, 2001 and 2003 and 2005. Future Mars Landers will draw their power from photovoltaic cells and have batteries for reserve power. As a result, significant power will only be available. during sunlit hours, which will vary depending on landing latitude and time of year. While batteries can be used to provide minimal power over night the power they can supply is limited, and furthermore, they must be protected from very low tempt] atures at night. It is exactly when temperatures are lowest that the least power is available for heaters to maintain the warmth of key components.

In order to cope with this problem, the Mars Pathfinder mission to be launched in December of 1996 will house electronics and batteries within enclosures which are very effectively insulated. The Mars Rover on that mission will include Radioisotope Heating Units (RHU's) which provide 2.8 Watts of continuous heating. RHU's produce a considerable amount of heat for their weight (~ 1 W per 50 g). Because mass and volume is limited for rovers, the Mars Rover will use aerogel as insulation in a structure called the Warm Electronic Box (WEB) (5,6). However, RHU's are no longer being produced and arc not expected to be used for any future U. S. missions. This paper will discuss an approach for maintaining thermal control of electronics for limited power missions without RHU's. The primary application are lander based science platforms and independent stationary scientific instruments such as penetrators or proposed in-situ resource utilization (ISRU) chemical generation plants

Without RHU's to provide heat overnight, such warm electronics enclosures (WEE) on lander based science platforms will go through very wide temperature swings during the diurnal cycle. Therefore, post-1998 Mars landers face **a** potential crisis in thermal control. Based on recent modeling conducted at JPL, it is believed that one way to provide. thermal control in the absence of RHU's is to employ a design approach in which a thermal capacitor is used. The thermal capacitor is charged by heat collected during the day when the sun shines, and the thermal capacitor is discharged by releasing heat at night to significantly reduce the diurnal temperature variation in an electronics/battery enclosure. There is a ready source of heat during the day because the photovoltaic arrays associated with the lander operate above 10011 temperature, and **the** structure for these solar arrays may be regarded as additional heat sources for our needs during the day. Thermal energy can be stored efficiently as latent heat of fusion in a phase-change material (PCM) which undergoes repeated cycles of melting and solidification when heated and cooled to temperatures above and below the material melting temperature. Dodecane (a paraffin wax), with its melting point of about, 1 () °C and good crystallization tendencies, is a possible candidate for our application. Dodecane has a latent heat of fusion of 263.5 KJ/g. Heat can be transported from the solar arrays to the PCM within the enclosure by means of a miniature heat pipe filled with an organic working fluid such as butane.

Even though PCM is a very appealing approach to serve as the thermal capacitor on paper, **the** application of PCM for heat storage has been problematic for several reasons. Chic is (hat it is necessary to supply and remove heat from all parts of the PCM, and this in turn requires good conduction heat transfer within the bulk of the PCM. Secondly, there is always a significant change in volume when a material melts or solidifies, and if the voids left by a previous solidification are not fairly uniformly distributed, large stresses can build up locally upon subsequent melting if no voids are available to a region of PCM to allow volume change. Thirdly, many materials tend to supercool below their melting points without crystallization, unless nucleation sites are present as crystallization starting points.

Energy Science Laboratories, Inc.(ESL), has developed a unique solution in designing the structures for PCM panels which overcomes these. three problems associated with using PCM as a thermal capacitor It involves a network of high thermal conductivity carbon fibers which occupy perhaps 5% of a volume. PCM is poured in to this matrix, which holds the PCM with capillary forces Heat transfer throughout tile.PCM region is rapid due to the network of carbon fibers. Voids tend to collect at fiber tips and thusget distributed fairly uniformly throughout the bulk of the PCM. Furthermore, the fibers also act as nucleation points for solidification, thus reducing supercooling. We have used this material in our system for a highly efficient PCM heat storage.

Experimental.

A generic design approach has been developed and tested utilizing phase change materials (PCM) and a diode heat pipe (DHP) to achieve thermal control of warm electronic enclosures that will maintain electronics, batteries, and instruments between -40 to 40 °C for future Mars landers. A phase change material (e.g., Paraffin wax- Dodecane) was used as the thermal capacitor working in conjunction with a diode heat pipe (Butane as the working fluid). This was experimentally tested to demonstrate thermal buffering of a typical warm electronic enclosure for temperature variations for a mid-latitude Mars environment. The advanced PCM panels consist of a sandwich panel design with an interlocking carbon fiber core which is filled with a suitable phase change material. The fibers provide structural stiffness, and prevent the PCM from forming voids or migration of voids by capillary action. For the panels used in this test, the PCM mass fraction was 54%. With this design, a PCM mass fraction increase to 70% has been achieved,

A schematic of the WEE and thermocouple locations are shown in Figure 1. This is a prototype electronics enclosure consists of six PCM panels, one of which has a diode heat pipe. The PCM panels were enclosed in an insulative foam box. 1 t was tested without any electronics inside. Instead, the enclosure was provided with aluminum plate masses representative of mission electronics, and batteries, respectively. Variable power electric heaters were used to simulate electronic power duty cycles were to mounted on these plates. All temperature measurements were made with thermocouples. Sixteen Type E (Chromel-Constantan) 30-gauge thermocouples were used. The total mass of the PCM panels in the WEE was 950 grams, and a781 gram aluminum block was included inside to simulate the thermal mass of electronics. A resistive heater was. attached to the aluminum block. A second reference box was also constructed. It included 934 grams of aluminum to represent the. PCM thermal mass and 800 grams of aluminum to represent the electronics mass. It had a total of five thermocouples, one on the interior heater block, and two on internal surfaces, and two on external surfaces. A Minco film heater is attached to the 800 gm aluminum block. The Rohacell foam box has a mass of 355 grams Both the WEE and the reference boxe were cove.JL'd with aluminum foil to provide a low emissivity exterior surfaces.

Testing conducted consisted of thermal cycling at ambient atmospheric pressure with variable power levels. Subsequent testing of the WEE consisted of a more exact diurnal cycle reproducing the Mars 1O torr ambient pressure, thermal environment, and variable power duty levels. The one atmosphere tests conducted showed that the panel performance are repeatable over a large number of thermal cycles. This testing measured temperature excursions to assess PCM heat transfer and other relevant physical properties such as the melting /solidification temperature. This also demonstrated fabrication and materials compatibility of PCM panels. The results of this testing will not be presented here.

The simulated Mars environmental testing of the WEE and a reference enclosure was conducted in a 0.9 m diameter x 1.8 m horizontal thermal-vacuum chamber. The diurnal cycle was shortened from 24.6 hours to 24 hours, with sunrise occurring at the 6 hr mark of our test and sunset occurring at 18 hr point of our cycle. The conditions for a 24 hr diurnal cycle matched the temperature profile for the Mars Pathfinder landing site and had an ambient pressure of 8 torr N_2. The two enclosures were suspended in the center of the chamber. The WEE was to the. rear of the chamber, with the. heat pipe extending vertically from the bottom. The reference box was placed in the fore.ground. The temperature profile is shown in Figure 2. The Mars diurnal temperature cycle was repeated for three days, at which time the chamber was warmed up and opened.

Power profiles were applied to the heaters to simulate expected heat rejection from electronics and internal heating. These profiles are similar to the heat from the MFEX Rover (5), scaled down to match the dimensions of the WEE. Two heating cycles were used during this test. The first being 8 Watts maximum power for the first day of the test. For days 2 and 3, a maximum of 6.4 Watts was applied. The power supplied to the WEE was split with 62.5% of the. power to the internal aluminum mass, and 37.5 % of the power to the diode heat pipe. For the reference enclosure, all heat was to the internal aluminum mass. Power to the heaters was initiated at the 6 hr point of the diurnal cycle. The power to the heaters was stepped up to full power in three one hour increments, with full power applied for six hours. This was followed by stepping down the power in three one hour increments, with power off at the 18 hr point. The total heater energy applied during day 1 was 72 W-hours, whereas for days 2 and 3 the total heater energy was 57.6 W-hr. Figure 3 shows the. internal temperature profiles inside the WEE and Figure 4 compares the temperatures from the reference box for the. three day test.

For the initial conditions of the test, the shroud was cooled to -80°C under 10 torr vacuum, and held at these conditions for 6 hours. For reference, all times will be referred to the 24 hr shortened Mars Diurnal time scale, with sunrise occurring at of 6:00 am, sunset occurring at 6:00 p.m., and midnight occurring at the 24:00 point. The ambient temperature and interior electronics power profile was then initiated at the Mars equivalent time of 6:00 am. During the cooldown, the internal temperatures reached -10°C, the solid-liquid transition temperature of dodecane, the phase change material in the PCM panels. All internal temperatures were closely grouped within ±3°C. Peak power of 8 Watts occurred at 9:00 am, and remained at peak power until 9:00 p.m. The interior temperature reached a maximum of 18 °C. This peak temperature occurred at the equivalent of 3:00 p.m. The interior had cooled down to 10°C and began the phase change at about midnight. The transition lasted until 4:30 am, for a duration of 4.5 hours. The lowest internal temperature during the first day was -18 0(, occurring at 8:30 am into the second day. The total energy used for heating during the first day was 72 watt- **hours.**

Evaluating the performance of the WEE at 2 power levels provided a better understanding of the phase transitions centered around the melting point of the dodecane phase change material. Again, for the second day the. interior temperatures were well grouped within a few degrees. For the lower heater power levels, a thermal lag was observed between the thermocouple on the interior surface and the then no couple between the PCM panel and the wall. The maximum interior temperature observed was -3°C at about 1:00 p.m. The interior cooled during the afternoon and began the PCM transition at 10:00 p.m. The transition lasted until 4:00 **am,** for a duration of" 6 hours. The lowest internal temperature was - 25°C, which occurred at 8:00 am.

The third day had the same power duty cycles as the second day, and the WEE pm-formed similarly. The maximum internal temperature was - 5°C which occurred at about 1:00 p.m. The phase change transition began at 10:00 p.m. and lasted until 4:00 am, for a 6 hour duration. The coldest interior temperature was -28°C at 8:30 am of the fourth day. "This is a lower temperature than was observed than the morning of the third day, because no additional internal power was provided.

The interior and exterior temperatures showed a good degree of repeatability during the test, The panel with the heat pipe was always the warmest, with the side, top and bottom panels having a small thermal lag. In general, all panels were well coupled thermally. During the first day, the internal gradients were less than two degrees during the phase transitions. The largest internal gradients occurred during the melting of the PCM material, and were observed on the panel that had thermocouples #7, 8, 9 10, and 14. The largest gradient was 4 degrees across the PCM panel during melting between thermocouples 7 and 8, with less than a one degree gradient between the top (TC #9) and bottom (TC #1O) on the interior surface on the PCM panel. This implies that the dodecane melted uniformly from the interior to the exterior. For the second and third days of the test, the gradient across the PCM panel decreased to two degrees between thermocouples 7 and 8 during the freezing of the PCM and was four degrees during the melting of the PCM. The gradient across the insulation was a maximum of 23°C during each of the three nights.

Study of the performance of the reference box helps in better understanding the advantages of including the PCM panels to moderate temperatures within the WEE. For the reference box during day 1, the maximum internal temperature was cm the heater block with a temperature of 59°C. This occurred near the end of the peak power for the day. The maximum surface temperature was 33 °C, with 1O degree gradient across the insulation, The lowest internal temperature during the night was - 40°C. For the day the total variation between the warmest and coldest temperature was 99°C. Days 2 and 3 behaved similarly, with no noticeable difference in their behavior The maximum internal temperature of 44°C was on the heater block, with the highest interior surface temperature of 25°C. The lowest interior temperatures were -40 and .12°C respectively for days 2 and 3. The gradient across the insulation decreased to 8°C. The total variation between the warmest and coldest temperatures were 84 and W°C for days 2 and 3 respectively.

The experiment clearly demonstrates that the PCM panels provide for moderating the interior temperatures. The maximum temperature excursion of the WEE was 34°C for day 1 and 23°C for days 2 and 3. This is significantly lower than the 99 and 40 and 42°C variation for the reference box. It is obvious that this significantly reduced thermal variation minimizes thermal stress on electronics, electrical interconnects and the batteries. This is a significant feature when developing instrumentation that must have an extended life during future Mars missions.

Finite Element Modeling

The objective of developing a finite element model (FEM) of the warm electronic enclosure design was to use. the FEM to further develop and optimize the design of the WEE The WEE was modeled using ANSYS finite element software. One half of the physical test enclosure is modeled because of the symmetry of the design. The FEM model accurately represents the dimensions and material properties of the WEE enclosure as evaluated in the 8 torr thermal vacuum test discussed earlier. The properties incorporated into the FEM model include:

- The dodecane phase-change compound contained within the PCM panels of the enclosure.
- The Rohacell foam used as insulation for the enclosure.

- The aluminum exterior emissivity surface of the enclosure.
- The. interior heat source and the heater applied to the diode heat pipe.
- Convective heat transfer between the WEE and the test chamber.
- Thermal radiation exchange between the inside walls of the enclosure.
- Thermal radiation between the exterior insulation surface and the test chamber.

The model material properties were taken from known values by comparing model results to actual test hardware performance The data from day 2 were used as the standard which the model is to represent. '1 'he model material physics] properties were taken from known values for materials well defined, such as aluminum. Other model properties were first estimated using engineering correlation's and then improved by comparing model results to test data

The FEM model consists of the following type of elements:

- 8-node "bricks" for the core material of the panels, for the Rohacell insulation, and for conduction between panels where they overlap
- 4-node "shells for the panel face sheets and closeouts
- Point thermal mass on 6 nodes to represent the heater block
- Superelement (two radiation matrices), 8 emissivity for inside surfaces of enclosure, 0.2 on outside surfaces

Aluminum panel face sheets and close- outs are represented by thermal conductivity, density and heat capacity. 'l'he Rohacell insulation is represented in the same way, except that the thermal conductivity really represents the series conductance of the foam insulation itself and of the small air gaps from the enclosure to the foam and of the foam to the outer aluminum foil. The composite properties 01 the carbon fiber and dodecane are represented by thermal conductivity and enthalpy. The melting and freezing phase change transition of dodecane is modeled as occurring over a one degree span, fr om -10 to -9 °C. In order to have the model perform similar to the test hardware, the following properties variables were adjusted by trial:

- Thermal conductivity of insulation and air gaps
- Convection coefficient at outside model surface
- Emissivity of outside model surface
- Enthalpy of the carbon fiber / dodecane matrix
- Heat capacity of insulation material with entrapped gas from the atmosphere

"]'he ANSYS FEM model had the chamber air and shr oud temperature, and the applied heater power duties as the program input loads These loads are taken from the day 2 data and applied to the model in a series of 30 minute steps except as needed for correct heater on /off times.

The solution is run as a transient non linear thermal analysis by applying the loads in a series of 196 steps. Model temperatures over time are extracted at nodes which coincide with thermocouple. locations on the test hardware in Figures 5 and 6. The model temperature is compared to test positions for TC 4, TC 7 and TC 14 of the WEE. The mode] is seen to correspond well to test, with some improvement expected as model properties are readjusted. Figure 7 shows model temperatures in steps of 45 minutes into the melting of the PCM . The plot illustrates the progressive melting of phase-change material.

The FEM model is seen to function in a realistic manner, with the. capability to further refine the results relative to the experimental lc'suits. The model exterior surface temperature (at TC 14) follows the experimental rc.suits quite well, with only a 2 to 3 degree maximum variation front the test results This model temperature has been seen to be strongly affected by the convection coefficient (.039 W/m "K for this ran) and little by including radiation at .1 emissivity.

Based on the model response for the heater block and the interior PCM panel temperatures (TC 4 and TC 7), the model heat capacity is close to that of the test hardware. Some of the variation at the heater block is expected to be due to **the likelihood** that the aluminum heater block is represented In an area some-what smaller than the actual size. The insulation thermal conductivity (.032 W/m°K for this run) can also be further adjusted and may be balanced by small changes in the heat capacity of the carbon fiber/dodecane.

The FEM model provides a low et):. ~ means to optimize the Warm Electronic Enclosure design by minimizing experimental testing. This modeling technique has application to the **design of** thermal enclosure hardware. PCM panel thickness and phase change compound mass, as well and insulation thickness can be quickly adjusted in a computer model. The thermal performance can be predicted and adjustments can be made in the design.

Summary

The use of phase change materials provides an efficient means to moderate temperat ures for electronic enclosures for future Mars landers. The graphite fiber P C M panel design eliminates prior cycle life problems of phase change panels, and provides an efficient thermal and structural configuration that can be integrated into a low mass structural design. Interior temperatures of electronic enclosures are moderated by the use of PCM panels, minimizing, thermal variations of an insulation only design. This behavior is predicable, and repeatable, and is easily modeled to **predict** thermal performance.

Acknowledgments

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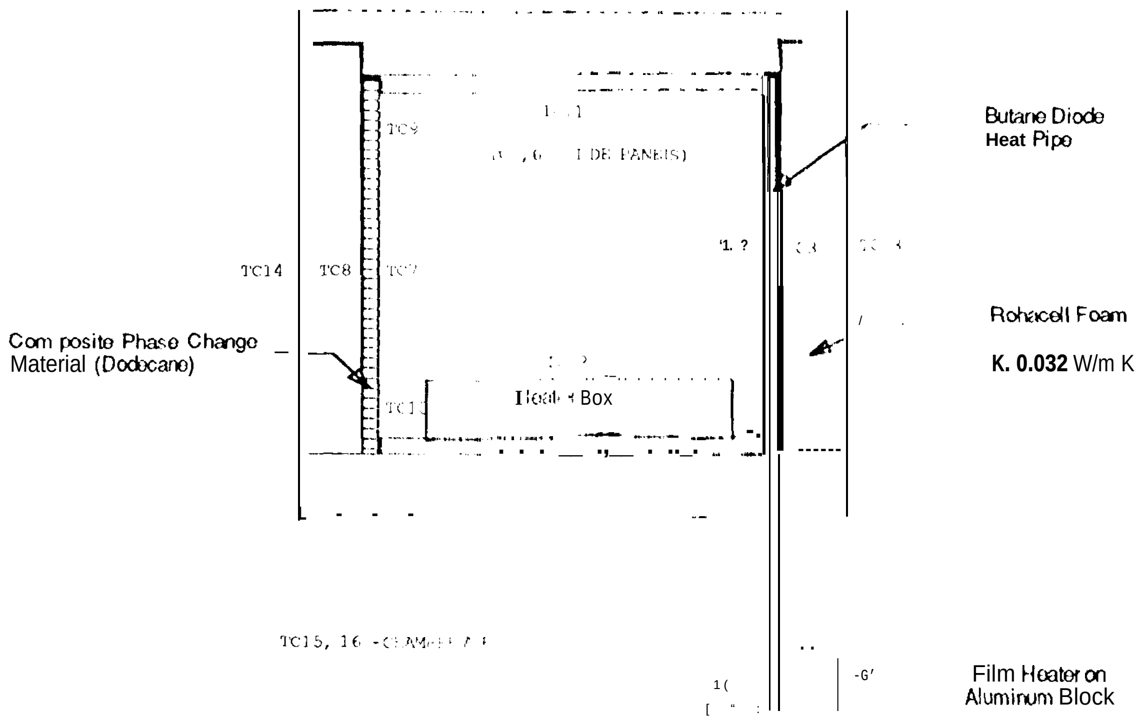

Figure 1: Schematic of the Warm Electronic Enclosure (WEE), and instrumentation used during the thermal-vacuum test.

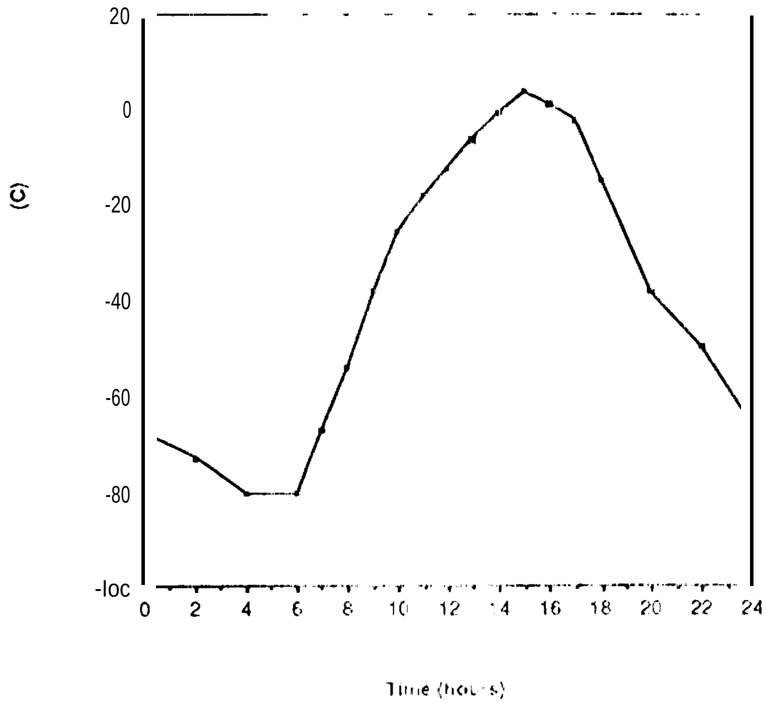

Figure 2: Diurnal temperature cycle used in the thermal-vacuum test

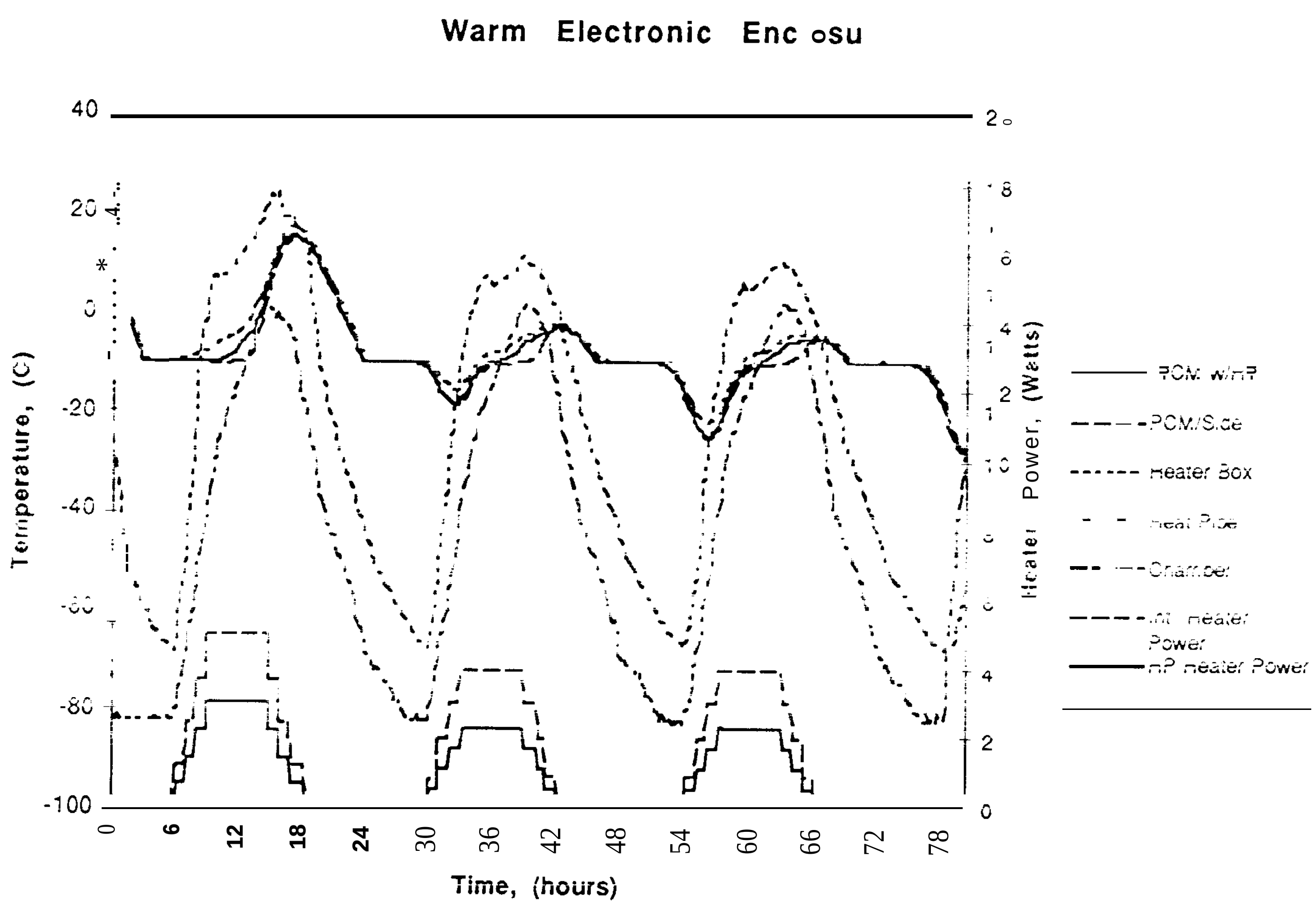

Figure 3: Internal temperatures of the Warm Electronic Enclosure during the thermal-vacuum test.

Reference Enclosure

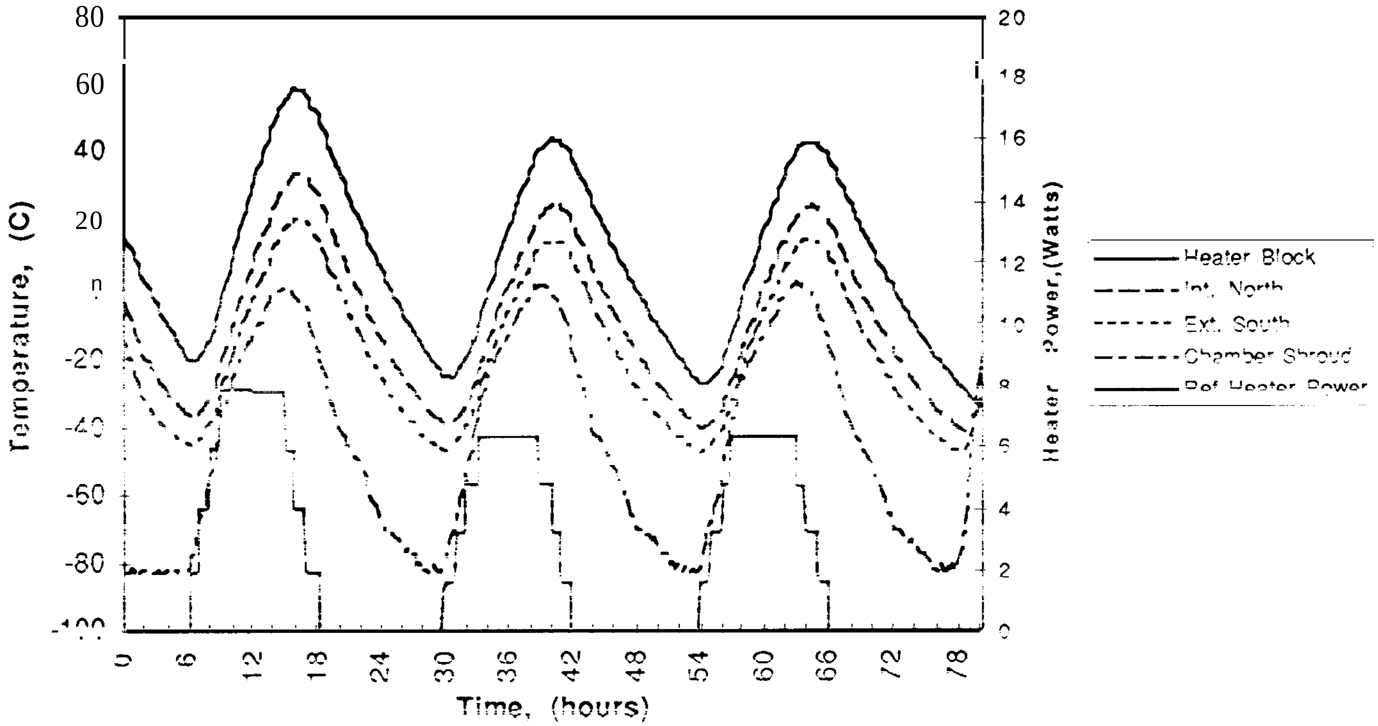

Figure 4: Temperature profiles of the reference thermal enclosure during the thermal-vacuum test.

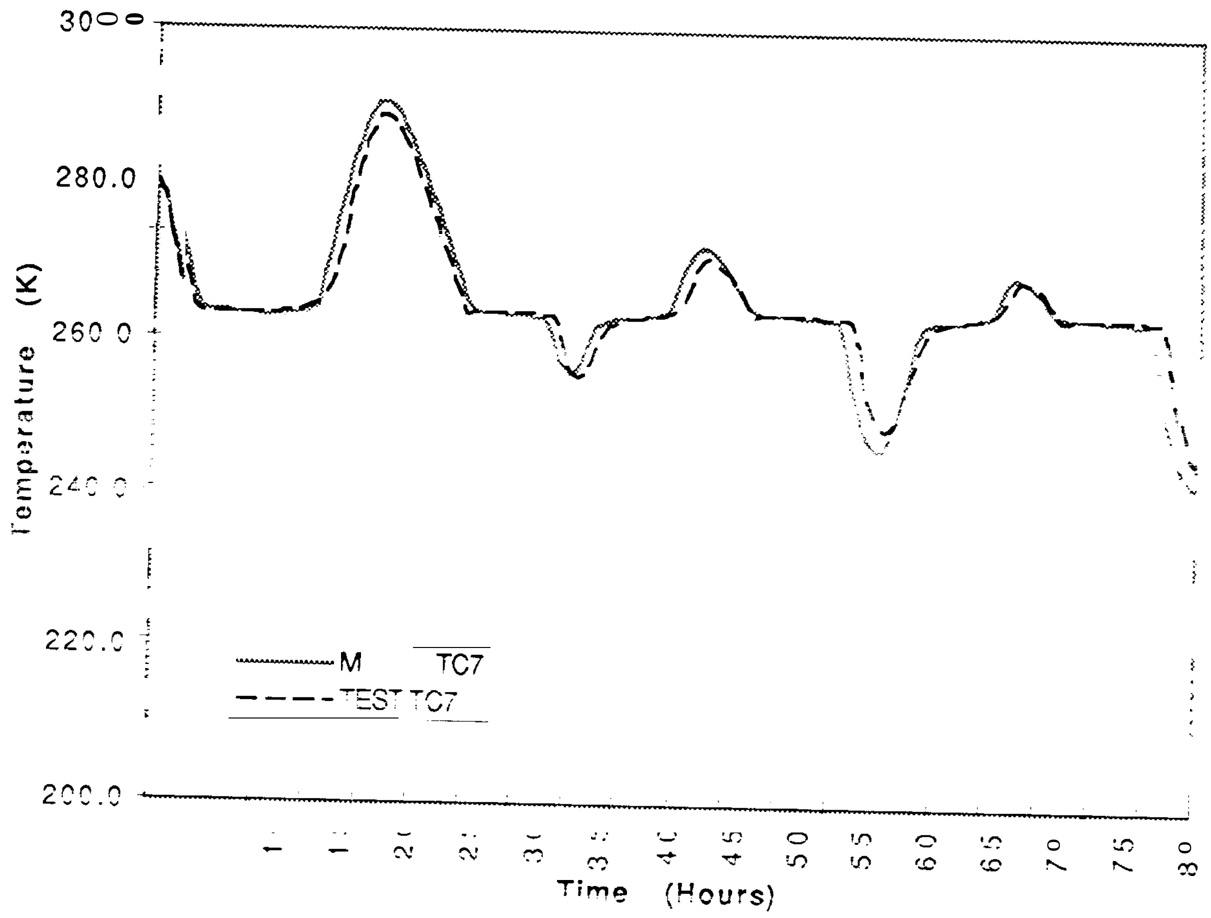

Figure 5: Comparison of the Finite Element od with the experimental test for the interior surface of the side wall PCM panel.

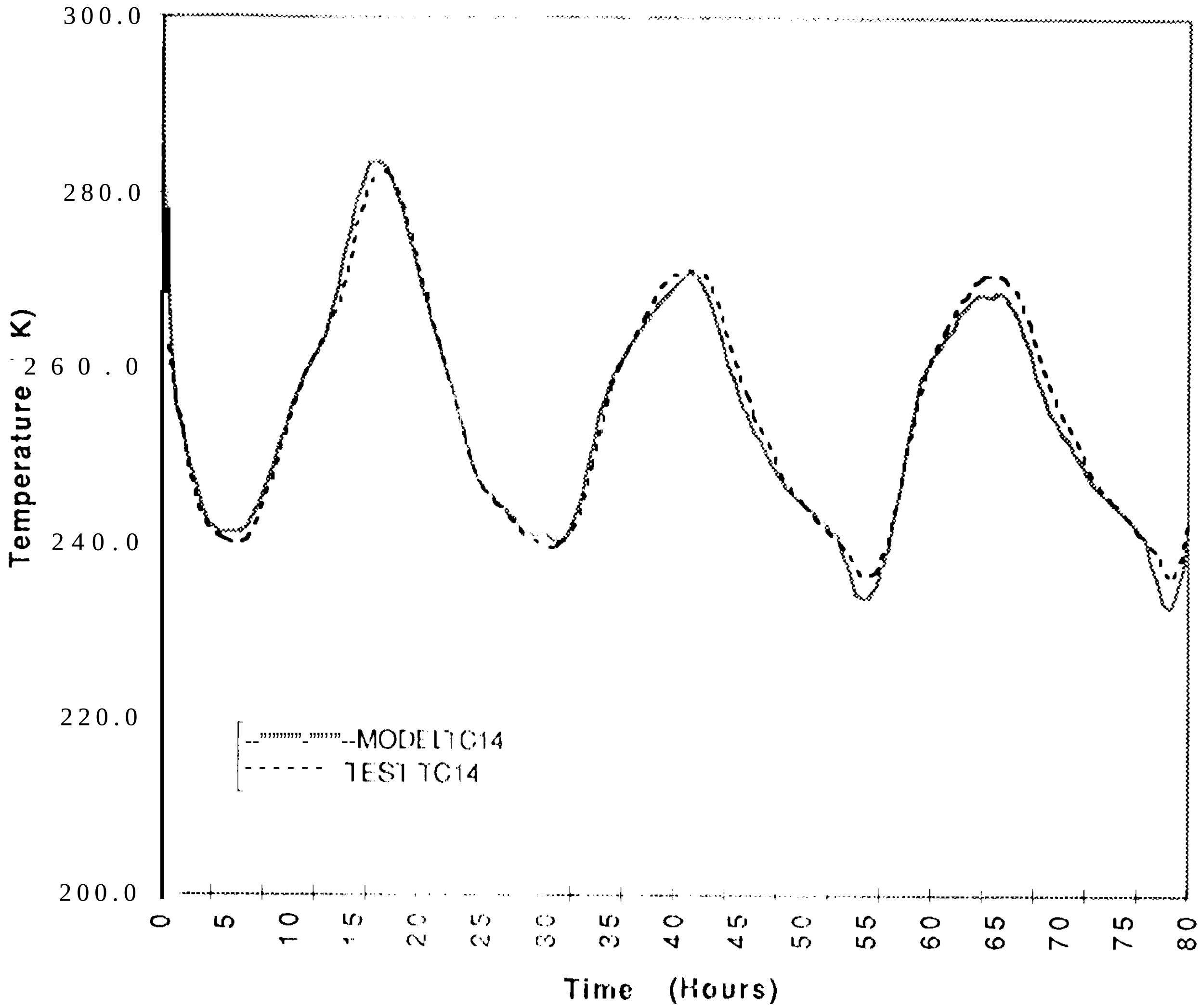

Figure 6: Comparison of the Finite Element Model with the. experimental test for the exterior surface of the side wall.

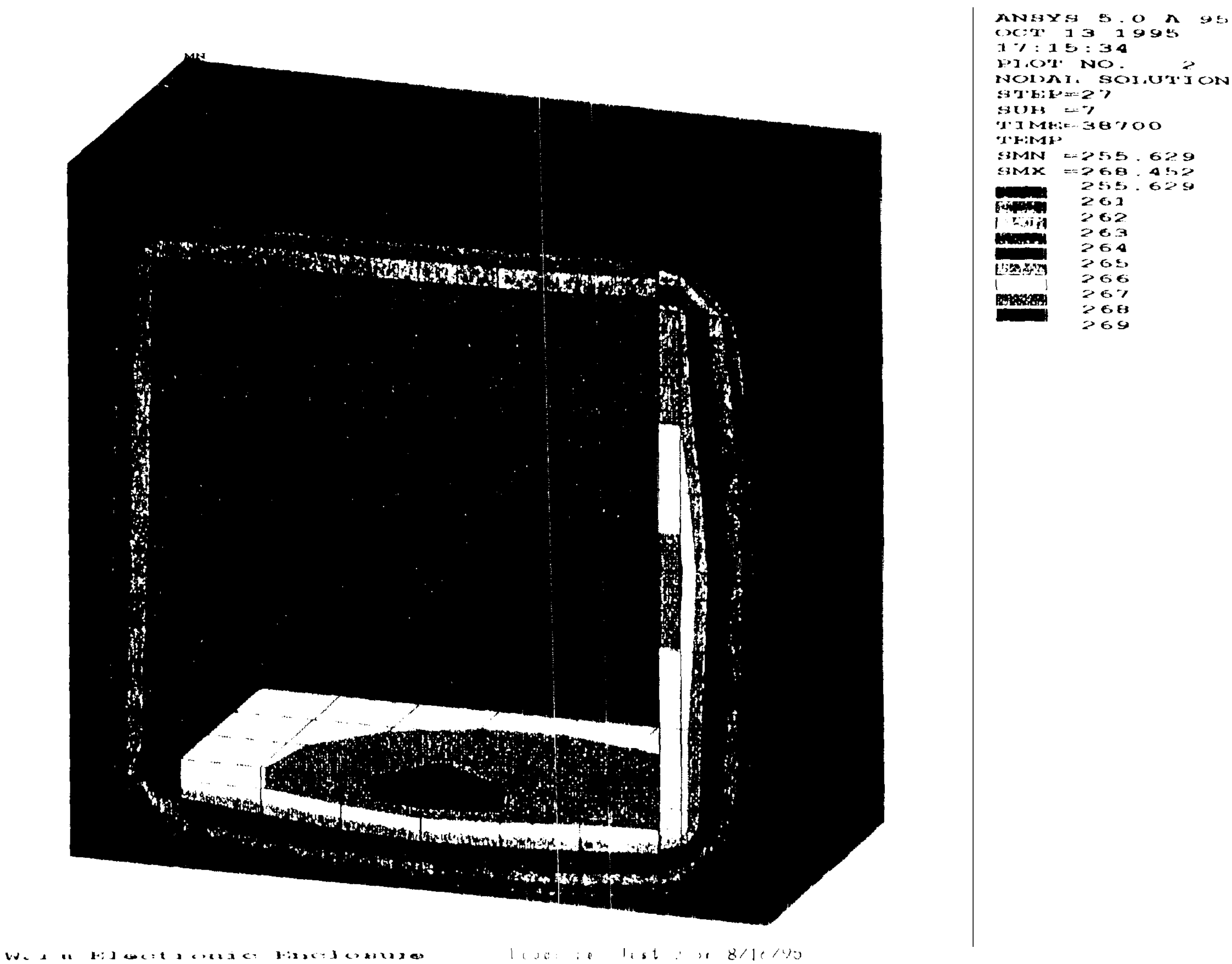

Figure 7: Results of the Finite Element Model of the WEE at 10 hours, 45 minutes into Day 1 of the 10 torr test showing progressive melting.